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Breanna L. Marmur
Iowa State University, bmarmur@iastate.edu

Theodore J. Heindel
Iowa State University, theindel@iastate.edu

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Abstract

The renewable energy industry relies on double screw pyrolyzers to convert cellulosic biomass into bio-oil. Bio-oil can then be converted into synthetic gasoline, diesel, and other transportation fuels, or can be converted into biobased chemicals for a wide range of applications. One of the processes by which bio-oil is produced in industry today is through fast pyrolysis, the fast thermal decomposition of organic material in the absence of oxygen. One type of pyrolyzer, a double screw pyrolyzer, features two intermeshing screws encased in a reactor which mechanically conveys and mixes the biomass and heat carrier media. The mixing effectiveness of the two materials in the pyrolyzer is directly correlated to the bio-oil yield — the better the mixing, the higher the yields. This study investigates the effects of varying biomass inlet concentrations on mixing effectiveness. Using 300–500 μm glass beads as simulated heat carrier media and 500–6350 μm red oak particles as biomass, a cold-flow double screw mixer with 360° of optical access and full sampling capabilities was used to collect mixing data. Advanced optical visualization and composition analysis paired with statistical analysis was used to evaluate the effects of varying the biomass inlet concentrations. Biomass inlet concentrations in terms of glass beads to red oak mass flow rate ratios (GB:RO) of 10:1, 20:1, 30:1, 40:1, and 50:1 were investigated, and correspond to biomass mass fractions of 9%, 4.7%, 3.2%, 2.4% and 1.9%. Both qualitative and quantitative analysis indicates that a counter rotating down pumping particle flow is best, and smaller biomass inlet concentrations noticeably reduce mixing effectiveness.

Keywords

Screws, Biomass

Disciplines

Energy Systems | Natural Resources Management and Policy | Sustainability

Comments

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EFFECT OF BIOMASS INLET CONCENTRATION ON MIXING IN A DOUBLE SCREW PYROLYZER

Breanna L. Marmur*
Iowa State University
Ames, Iowa, USA

Theodore J. Heindel
Iowa State University
Ames, Iowa, USA

ABSTRACT

The renewable energy industry relies on double screw pyrolyzers to convert cellulosic biomass into bio-oil. Bio-oil can then be converted into synthetic gasoline, diesel, and other transportation fuels, or can be converted into biobased chemicals for a wide range of applications. One of the processes by which bio-oil is produced in industry today is through fast pyrolysis, the fast thermal decomposition of organic material in the absence of oxygen. One type of pyrolyzer, a double screw pyrolyzer, features two intermeshing screws encased in a reactor which mechanically conveys and mixes the biomass and heat carrier media. The mixing effectiveness of the two materials in the pyrolyzer is directly correlated to the bio-oil yield—the better the mixing, the higher the yields. This study investigates the effects of varying biomass inlet concentrations on mixing effectiveness. Using 300-500 μm glass beads as simulated heat carrier media and 500-6350 μm red oak particles as biomass, a cold-flow double screw mixer with 360° of optical access and full sampling capabilities was used to collect mixing data. Advanced optical visualization and composition analysis paired with statistical analysis was used to evaluate the effects of varying the biomass inlet concentrations. Biomass inlet concentrations in terms of glass beads to red oak mass flow rate ratios (GB:RO) of 10:1, 20:1, 30:1, 40:1, and 50:1 were investigated, and correspond to biomass mass fractions of 9%, 4.7%, 3.2%, 2.4% and 1.9%. Both qualitative and quantitative analysis indicates that a counter rotating down pumping particle flow is best, and smaller biomass inlet concentrations noticeably reduce mixing effectiveness.

INTRODUCTION

Fast pyrolysis is the thermochemical conversion of biomass in the absence of oxygen [1]. One method of fast pyrolysis involves a biomass material being mixed with a heat carrier media, usually sand, in a double screw pyrolyzer to produce bio-oil [2, 3]. The mixing between the biomass and heat carrier media is an example of a granular flow. Bio-oil yield is dependent on the mixing effectiveness between the two granular materials, and thus, a thorough understanding of the particle mixing dynamics inside the double screw pyrolyzer is crucial to improving bio-oil yields [1].

Granular mixing processes appear not just in the renewable energy industry, but across a wide range of industries, from the pharmaceutical industry to the agriculture industry [4, 5]. Granular mixing processes often seek a high degree of homogeneity [1, 6], but the tendency of granular materials to segregate often hinders this goal [6, 7]. A number of reviews are available in the literature that provide a good overview of granular mixing processes [4, 5, 8]. Many researchers have focused on understanding the mixing dynamics of granular flows in mixers of various geometries [9-12]. However, much of the work done thus far has focused on mixers with relatively simple geometries and idealized particles. Some studies have focused on the mixing dynamics of granular flows inside single screw mixers [13, 14], but in fast pyrolysis, a double screw pyrolyzer is more effective than a single screw pyrolyzer [15, 16]. Kingston and Heindel [17, 18] investigated the mixing dynamics inside a double screw mixer to simulate the behavior of the granular materials in a double screw pyrolyzer. They identified operating conditions to increase the mixture homogeneity, and thus the mixing effectiveness for a fixed mass flow rate ratio.

The purpose of this study is to determine the effect of biomass inlet concentration on the mixing effectiveness of the double screw mixer. As fast pyrolysis is the thermochemical conversion of biomass into bio-oil, it is highly dependent on the heat transfer from the heat carrier media to the biomass media. Increasing the ratio of heat carrier to biomass media in the system may increase the rate of heat transfer into the biomass material, thus increasing potential bio-oil yields [1, 19, 20]. This study investigates the mixing effectiveness in a double screw mixer as the mass flow rate ratio between the heat carrier media and the biomass material is increased from 10:1 to 20:1, 30:1, 40:1, and 50:1. Qualitative optical visualization methods and quantitative composition analysis, as developed by Kingston and Heindel [17, 18], were used to assess the mixing effectiveness of the double screw mixer. At each mass flow rate ratio, three parameters were investigated: (i) screw rotation speed, (ii) dimensionless screw pitch, and (iii) screw rotation

*Corresponding author, bmarmur@gmail.com

orientation. The operating condition based on these parameters that led to the highest degree of granular homogeneity—and thus the optimized mixing effectiveness—was determined.

EXPERIMENTAL PROCEDURES

Experimental Setup

The experimental setup and procedures used in this study are the same as developed by Kingston and Heindel [18]. Only a brief summary is provided here.

The clear, laboratory scale cold-flow double screw pyrolyzer used in these studies is shown in Fig. 1 and will be hereafter referred to as double screw mixer. The double screw mixer was 3D printed out of a designer plastic material, VeroClear, a very rigid, clear plastic. This unique manufacturing method allows complete 360° optical access to the internal structure of the screw mixer. The characteristic length of the mixer was defined as the screw diameter, D=2.54 cm. The mixing length, L, was defined as the center of inlet port 2 in Fig. 1 to the beginning of the outlet ports, where L/D=10.

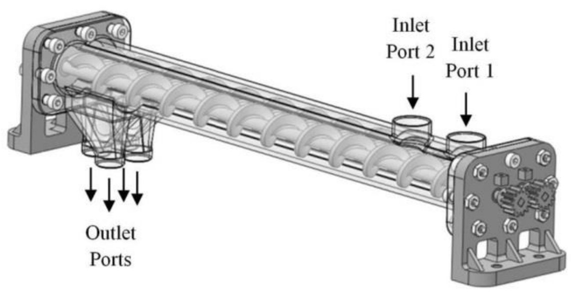

FIGURE 1: THE COLD FLOW, LABORATORY SCALE DOUBLE SCREW MIXER USED IN THESE STUDIES. ALL PARTS SHOWN ARE 3D PRINTED [18].

The biomass and heat carrier media were injected vertically into ports 1 and 2, respectively, located on top of the double screw mixer, two characteristic lengths apart. The two granular materials were fed into their respective inlet ports by two volumetric auger feeders (Tecweigh CR5).The exit stream was divided into four equal sections by four outlet ports located on the bottom of the double screw mixer. These outlet ports allowed the outlet flow of the pyrolyzer to be divided and sampled for composition analysis.

Granular Materials

The granular materials used in this study consisted of a biomass material (red oak chips, RO) in a size range of 500-6350 μm, and a heat carrier media (glass beads, GB) in a size range of 300-500 μm. The red oak was processed down to the specified size range using hammer mills and hand sieves. The red oak's true density was measured by a Pentapyc 5200e gas pycnometer (Quantachrome instruments) and found to be 1330 kg/m^3. Glass beads were chosen as the heat carrier media instead of the more traditional sand [3] because glass beads are much less abrasive than sand, a necessary feature to prevent undue scratches to the clear 3D printed double screw mixer. The glass beads had a density of 2510 kg/m^3, comparable to sand's (Quikrete No: 1961) density of 2680 kg/m^3 [17].

Operating Conditions

Table 1 summarizes the 14 operating conditions investigated at each mass flow rate ratio of (GB:RO) 10:1, 20:1, 30:1, 40:1 and 50:1, and is based on the conclusions made by Kingston and Heindel [17, 18]. Three parameters were tested, each at various levels: screw rotation speed, ω=20, 40, and 60 rpm; dimensionless screw pitch, p/D=0.75, 1.25, and 1.75; and screw rotation orientation, co-rotating (CoR), counter-rotating down pumping (CrtR DP), and counter-rotating up pumping (CrtR UP).

TABLE 1: THE 14 SELECTED OPERATING CONDITIONS INVESTIGATED IN THIS STUDY.

Screw Rotation Speed ω [rpm]	Dimensionless Screw Pitch p/D [-]	Screw Rotation Orientation
20	0.75	Counter, Up Pumping
		Counter, Down Pumping
	1.25	Counter, Up Pumping
		Counter, Down Pumping
	1.75	Counter, Down Pumping
40	0.75	Counter, Down Pumping
	1.25	Co-rotating
		Counter, Up Pumping
		Counter, Down Pumping
	1.75	Counter, Down Pumping
60	0.75	Counter, Down Pumping
	1.25	Counter, Up Pumping
		Counter, Down Pumping
	1.75	Counter, Down Pumping

The operating condition that optimized mixing, as determined by Kingston and Heindel [18], featured a screw rotation speed of ω = 60 rpm, a dimensionless screw pitch of p/D = 1.75, and a CtrR DP screw rotation orientation. The CtrR DP screw rotation orientation was determined to be the most advantageous screw rotation orientation, regardless of screw rotation speed and dimensionless screw pitch, and so all other operating conditions involving the CtrR DP screw rotation orientation were also investigated. One CoR screw rotation condition, determined previously to represent the standard operating condition, with a screw speed of ω=40 rpm, and dimensionless screw pitch of p/D=1.25 was chosen. Additionally, four CtrR UP screw rotation orientations were chosen: one with a screw speed of ω = 20 rpm, and a dimensionless screw pitch of p/D = 0.75, and three with screw speeds of ω = 20, 40, and 60 rpm, and a dimensionless screw pitch of p/D=1.25. The up pumping conditions were chosen based on the "poor" operating condition determined by Kingston and Heindel [18]. In total, 56 testing conditions were investigated in this study (14 operating conditions x 4 mass flow rate ratios). Note that the 10:1 mass flow rate ratio data were originally obtained by Kingston [17] and are used here in our analysis. In all tests, a 65% fill of the double screw mixer was maintained as this fill level is optimal to avoid problematic operating conditions [21].

Optical Visualization

To capture the dynamic mixing process within the double screw mixer, the method developed by Kingston and Heindel [18] was used. Four Panasonic HC-V700M high definition cameras, one each positioned to the top, left, right and bottom of the double screw mixer, were used to capture the dynamic mixing process. The cameras each have a 1920 × 1080 resolution and a frame rate of 60 FPS. To provide lighting, six 85 W compact florescent lamps were used to illuminate the mixing region, positioned three on either end, level with the screw mixer. The setup without the lights is shown in Fig. 2.

A sound spike was used to synchronize the four videos files. Adobe Premiere Pro CS6 video editing software was then used to combine the four separate video projections into one dynamic mixing video. Fig. 3 shows how the four independent projections are combined into one dynamic mixing video.

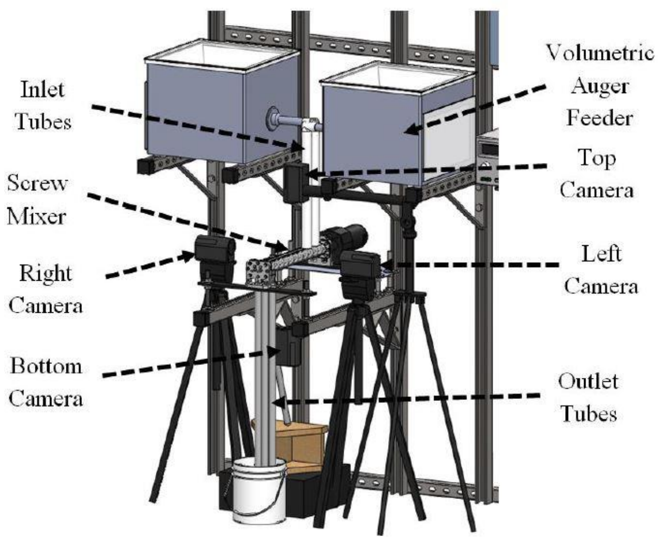

FIGURE 2: THE EXPERIMENTAL SETUP USED FOR OPTICAL VISUALIZATION OF THE DYNAMIC MIXING PROCESS INSIDE THE DOUBLE SCREW MIXER [18].

Composition Analysis

The mixing effectiveness within the double screw mixer was determined by the homogeneity of the mixture. The more homogeneous the mixture, the better the mixing effectiveness. Mixture homogeneity was determine by the method outlined by Kingston and Heindel [18].

The outlet stream of the double screw mixer was partitioned into four equal sections (outlet ports visible in Fig. 1) upon exiting the double screw mixer. To gauge the mixture homogeneity, the mixture composition of each sample was determined by calculating the true density of each sample and using an empirical correlation between mixture density and composition to determine the sample composition. The sample

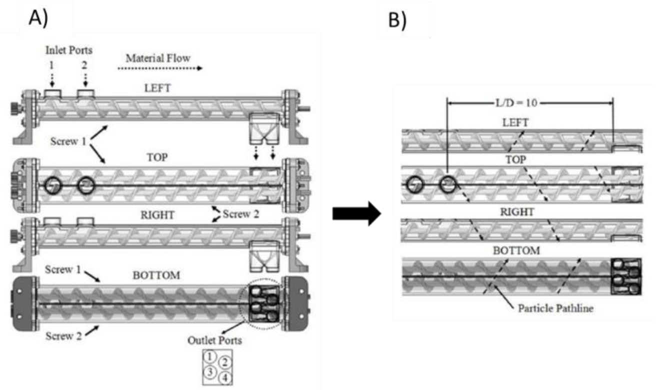

FIGURE 3: A) THE ORIGINAL FOUR PROJECTIONS OF THE DOUBLE SCREW MIXER. B) THE CROPPED AND ALIGNED IMAGES IN THE FINAL MIXING VIDEO [18].

compositions were then compared to each other, and across operating conditions, by calculating the standard deviation of the four outlet ports:

$$s^2 = \frac{\sum_{i=1}^{n} m_i (x_i - \overline{x_w})^2}{(\frac{N-1}{N})\sum_{i=1}^{n} m_i} \quad (1)$$

where n is the number of the ith sample, m_i is the mass of the ith sample, x_i is the composition of the ith sample, $\overline{x_w}$ is the mass weighted mean composition of the samples, and N is the total number of samples. The standard deviation was then used to calculate the statistical parameter, coefficient of variation, CV, which was used to gauge mixture homogeneity:

$$CV = \frac{s}{\mu} \quad (2)$$

where s is the standard deviation determined from Eq. (1), and μ is the theoretical mean of the outlet composition, which equals the inlet composition in an ideally mixed system.

The coefficient of variation, a dimensionless parameter that allows the variability in a series of numbers to be independently compared, regardless of the units or magnitude of the individual measurements, allowed the data from each mass flow rate ratio to be directly compared to each other. The CV is particularly good for comparing data sets with very different means, such as the differing biomass inlet composition theoretical mean mass fractions [22]. The biomass composition theoretical means stand for a perfectly mixed, perfectly homogeneous system, and were as follows: 50:1 was 1.96%, 40:1 was 2.44%, 30:1 was 3.22%, 20:1 was 4.76%, and 10:1 was 9.1%. When using the CV to determine the mixing effectiveness of the double screw mixer, a smaller CV indicates a more homogeneous mixture and greater mixing effectiveness. Therefore, a CV of zero is the desired result. Note that the samples collected from each exit port were collected at the same time. Also, three unique samples were collected from each exit port for each operating condition.

RESULTS AND DISCUSSION

Parameter Interaction

To understand the effect each operating condition has on mixing effectiveness, and to optimize the mixing effectiveness in the double screw mixer, the CVs of each operating condition were plotted against each other in a single plot. Figure 4 shows the three-way interaction between screw rotation speed, dimensionless screw pitch and screw rotation orientation for all investigated conditions. All five mass flow rate ratios have been plotted together in Fig. 4 to allow a direct comparison. The results of the 10:1 mass flow rate ratio are those of Kingston and Heindel [18]. To keep the graph concise and readable, only an averaging lines of the data points are provided in Fig. 4.

The CtrR DP screw rotation conditions for the 10:1 mass flow rate ratio featured the greatest mixing effectiveness, regardless of other parameters, as evident by the black lines for the CtrR DP conditions having generally lower CVs than the black lines (or dots) of the other screw rotation orientations in Fig. 4. This trend was observed in each higher mass flow rate ratio tested; quantitatively, the CtrR DP screw rotation orientations continued to provide the best mixing of the three screw rotation orientations tested, confirming the result of Kingston and Heindel [18].

However, increasing the mass flow rate ratio increased the double screw mixer's sensitivity to changes in screw rotation speed and dimensionless screw pitch. In the 10:1 mass flow rate ratio, the CtrR DP screw rotation condition showed little change in CV across changes in screw rotation speed and dimensionless screw pitch, indicating that mixing effectiveness was not affected by such changes. However, the higher mass flow rate ratios show a much greater variability in the CtrR DP screw rotation conditions across changes in screw rotation speed and dimensionless screw pitch. This indicates that as the mass flow rate ratio is increased, the mixing effectiveness of the double screw mixer is more dependent on screw rotation speed as well as dimensionless screw pitch, especially at higher screw rotation speeds.

The 10:1 mass flow rate ratio is the best mixing condition as it generally offers the overall lowest CVs. However, select CtrR UP conditions, specifically at 20:1 and 30:1 ratios, exhibit slightly lower CVs, and thus better mixing, for this orientation. A slight advantage for the higher mass flow rate ratios was also observed in the CtrR DP screw rotation orientations at dimensionless screw pitches of $p/D=1.25$ and screw rotation speeds of $\omega=40$ and 60 rpm. Especially at $\omega=60$ rpm, the higher ratios consistently offer lower CVs than the 10:1 ratio, with the 50:1 ratio offering the lowest CV and thus the greatest mixing effectiveness. However, for these operating conditions the actual difference between mass flow rate ratios is within the error bars (as discussed later).

The trends observed in the quantitative three-way interaction plot were also qualitatively observed in the dynamic mixing videos, of which snapshots are provided in Fig. 5. Again, the 10:1 mass flow rate ratio condition is from Kingston and Heindel [18]. In Fig. 5, the materials travel from left to right, the RO appears brown and the GB appear grey. However, due to the reduction of RO in the system at higher mass flow rate ratios, the RO is difficult to visualize in some of the snapshots. Only one operating condition is represented in Fig. 5, shown across all mass flow rate ratios. Even though only one set of snapshots is provided, conclusions presented here are based on thorough analysis of all recorded dynamic mixing videos.

At each mass flow rate ratio, the CtrR DP screw rotation orientations showed better mixing than the other two screw rotation conditions tested. The CtrR DP conditions, of which one condition is shown in Fig. 5, showed an even distribution of RO throughout the system with no agglomeration accumulation. The CtrR UP and CoR screw rotation conditions, however, showed large agglomerations of RO on the tops and sides of the flow. These agglomerations of RO are due to the natural tendency of the two materials to segregate and demonstrate poor mixing. All dynamic mixing videos captured indicate that, qualitatively, mixing effectiveness is increased for the CtrR DP screw rotation condition.

Due to the nature of the higher mass flow rate ratios, very little RO was present in the system at the higher ratios. This made optical visualization limited because of the preponderance of GB in the system. Because of this, the conclusions of the composition results—that increasing the mass flow rate ratio increases the systems sensitivity to screw rotation speed and dimensionless screw pitch, and that increasing the mass flow rate ratio decreases mixing effectiveness—can be neither supported nor unsupported by the dynamic mixing videos.

Uncertainty analysis

An uncertainty analysis was performed to calculate the amount of uncertainty associated with computing the coefficient of variation. The standard error of the coefficient of variation was used, an empirically calculated error that represents the maximum possible error in the data set [22]. The calculated standard errors were quite large and ranged from 0.03 to 0.18 with an average of 0.09; hence the error bars, when plotted on the three-way interaction plot, often overlapped each other. This indicates that our ability to differentiate the results from one mass flow rate ratio to another may be limited. However, close analysis of the individual data points indicate that the results of each mass flow rate are clustered together and remain distinct from other mass flow rate ratio data points, indicating that the trends observed in the averaging lines of Fig. 4 are consistent and represent actual mixing behavior.

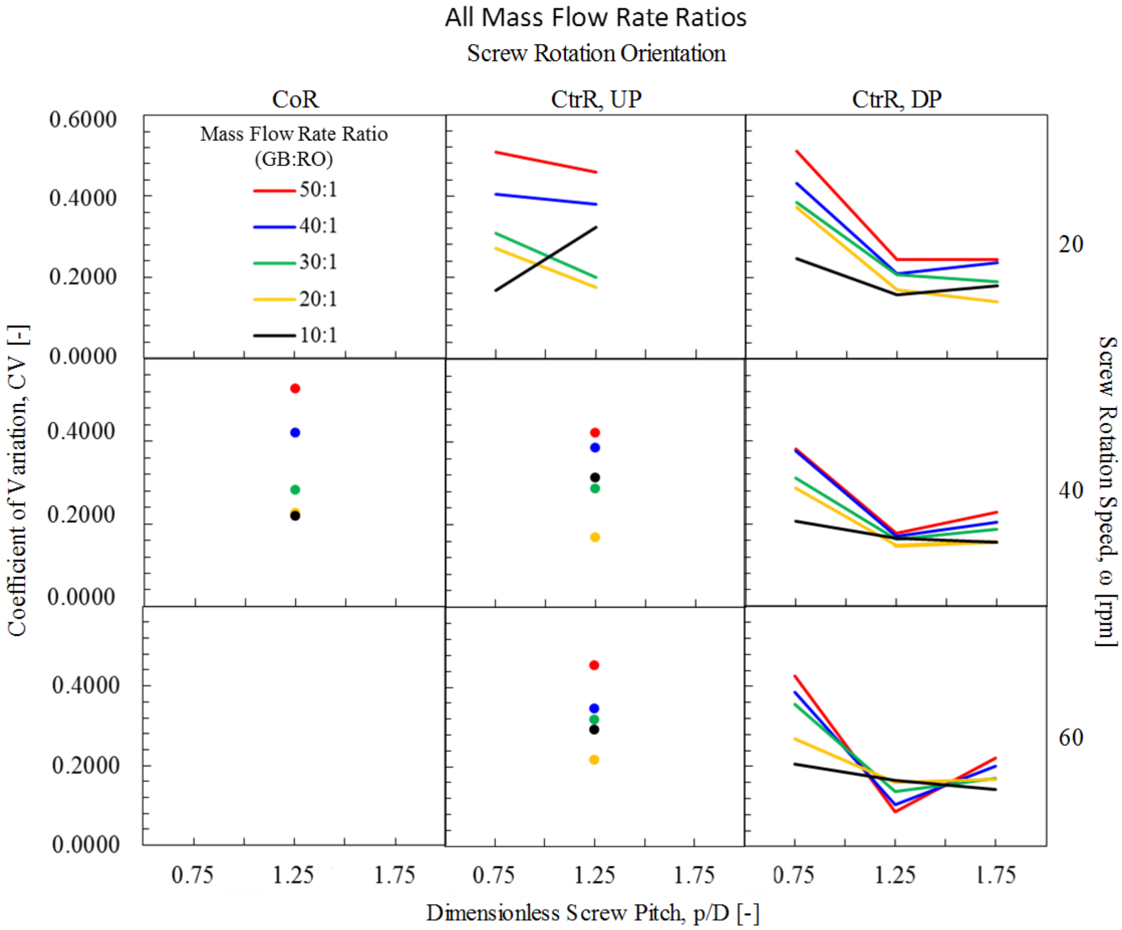

FIGURE 4: THE COEFFICIENT OF VARIATION AS A FUNCTION OF THE THREE WAY INTERATION PLOT BETWEEN SCREW ROTATION SPEED, DIMENSIONLESS SCREW PITCH, AND SCREW ROTATION ORIENTATION. TO AID VISUALIZATION, ONLY THE AVERAGING LINE OF EACH TEST CONDITION IS SHOWN. A LOWER CV INDICATES BETTER MIXING. THE 10:1 DATA CAME FROM KINGSTON AND HEINDEL [18].

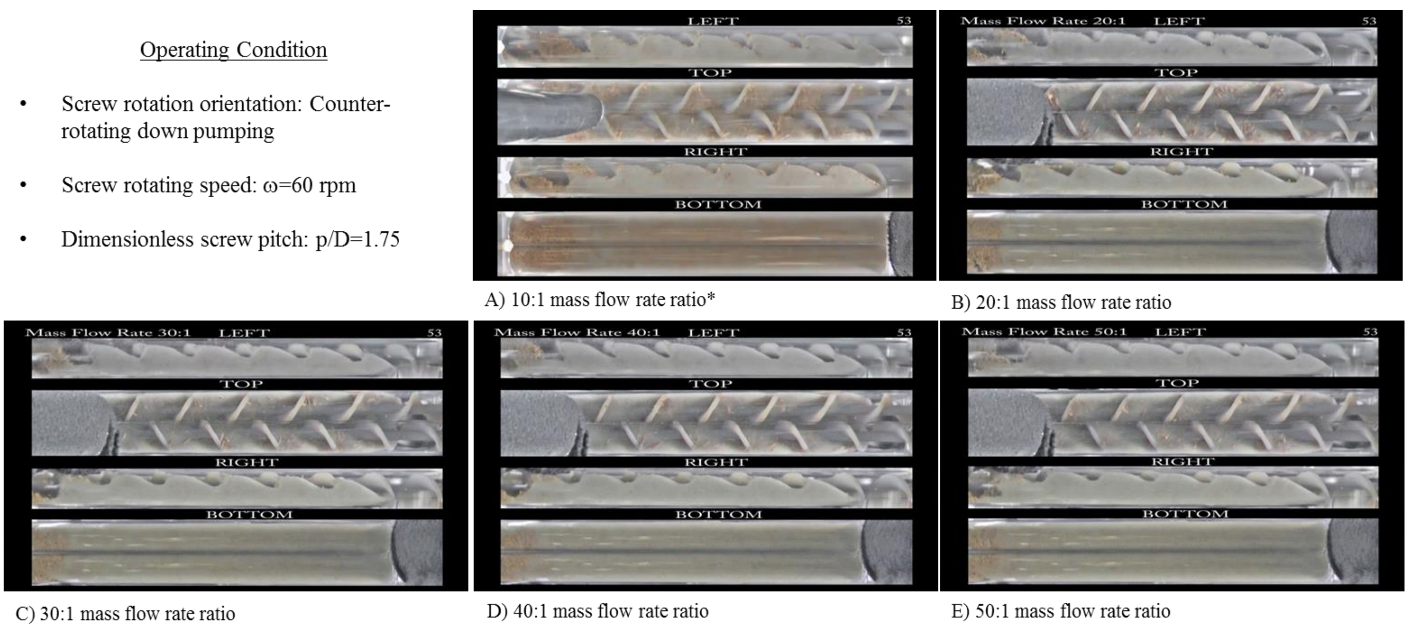

FIGURE 5: SNAPSHOTS OF THE DYNAMIC MIXING PROCESS ACROSS ALL FIVE MASS FLOW RATE RATIOS FOR ONE OPERATING CONDITION. THE 10:1 MASS FLOW RATE RATIO, A), IS FROM KINGSTON AND HEINDEL [18].

CONCLUSIONS

This study investigated the effects of the mass flow rate ratio between two granular materials on the mixing effectiveness in a double screw mixer. Both quantitative composition analysis and qualitative optical visualization was used to assess mixing effectiveness. Observations of both indicate that the counter-rotating down pumping screw rotation condition is the optimal mixing condition at any mass flow rate ratio. Furthermore, as the mass flow rate ratio increases, the dependence on screw rotation speed and dimensionless screw pitch for optimal mixing increases. Most importantly, increasing the mass flow rate ratio tends to decrease the mixing effectiveness of the double screw mixer. However, if higher mass flow rate ratios are required, select operating conditions, specifically the counter-rotating down pumping screw rotation condition at a screw speed of ω=60 rpm and a dimensionless screw pitch of p/D=1.75, offer improved mixing effectiveness at higher mass flow rate ratios. The results of this study can aid in the design of double screw pyrolyzers to optimize mixing effectiveness, and therefore mixture homogeneity, which could in turn lead to higher heat transfer rates and potentially higher bio-oil yields.

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